

WHITE PAPER

Proposal to Determine the Frequency of Long-Period Planets in the Habitable Zone of Solar-like Stars

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ABSTRACT

It is recommended that the Kepler Mission continue the observation of Kepler-Objects of Interest (KOI) in the current field-of-view to obtain a reliable estimate of eta-Earth. Currently no Earth-size planets in the HZ of a solar-analog have been found. Although the analysis of the four years of data already in hand, but not yet fully analyzed is expected to show one or more such planets, additional discoveries of planets with orbits at least as long as those associated with the habitable zone (HZ) are needed to increase the reliability of eta-Earth. The degradation of the photometric precision because of the loss of two reaction wheels is likely to prevent the discovery of Earth-size planets in the HZ of G dwarfs, but it is possible that the precision will be sufficient to detect larger planets with long orbital periods. It is proposed to use an interpolation techniques that incorporates a full range of planet sizes, orbital periods, and stellar properties is one of several methods that could provide a useful estimate of eta-Earth and its uncertainties.

DESCRIPTION OF THE SCIENCE PROJECT PROPOSED

The Planetary Astronomy Decadal Survey stated that it is vital to determine “key issues such as planet frequency” within the next decade. To achieve these goals, the community must “understand the demographics of other planetary systems, in particular to determine over a wide range of orbital distances what fraction of systems contain Earth-like planets”. The NASA Space Mission Directorate (SMD) goal for astrophysics is to “discover how the universe works, explore how the universe began and developed into its present form, and search for Earth-like planets.” This proposal directly addresses the SMD goal of searching for Earth-like planets.

The primary goal of the Kepler Mission is to determine the frequency of Earth-size planets in the HZ of solar-like stars (i.e. eta-Earth). To detect a possible planetary candidate by the Kepler analysis pipeline, at least three transits must be detected and because approximately 150,000 stars must be monitored without a false-positive event due to a statistical fluctuation, a multiple-event statistic (MES; i.e., the combined SNR for all transits) with a value greater than 7.1σ is required. At a threshold value of 7.1σ , 50% of the events are recognized while the recognition rate for a set of transits with a $MES = 8.1\sigma$ is 84%. A 4-year mission provides 2 to 4 transits of planets in the HZ of stars like the Sun. For Earth-size planets in one year orbits around quiet G2 dwarfs, 4 transits can produce an 84% recognition rate. It is expected that the analysis of the data already in hand will produce a few such detections and thus a rough estimate of eta-Earth. Unfortunately observations have shown that most ($\sim 2/3$) G-dwarfs are twice as variable as the Sun. (See Figure 1.) It was quickly recognized that to get a more reliable estimate of eta-Earth, the Mission needed to be extended to observe more transits. Consequently, a proposal was submitted to the Senior Review panel who then recommended that the Mission be extended for an additional two to four years. This recommendation was accepted by the NASA Science Mission Directorate and the Kepler observations continued for several months before the loss of a second reaction wheel stopped further observations.

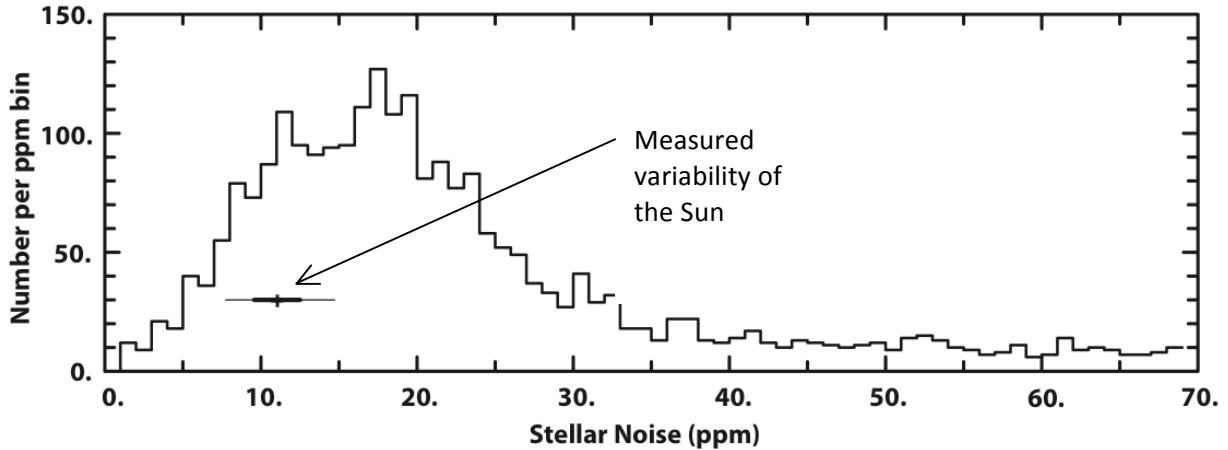


Figure 1. Measured variability for quiet dwarf stars between magnitudes 11.5 and 12.5 on the time-scale of several hours compared to that of the Sun (1). Although the Mission design assumed that most G dwarfs would be older and less variable than the Sun, the observations show that most quiet stars are substantially more variable than the Sun.

Adding to the difficulty of getting an accurate value of eta-Earth due to the more-variable-than-expected stars, is the fact that the range of orbital periods associated with the HZ of solar-like stars extends from 224 days to 770 days¹, i.e., to cover the full range of orbital periods requires at least 6 years of observations just to detect a minimum of three transits. Currently, the Kepler Mission has not detected any Earth-size planets orbiting in the HZ of a star matching the Sun. It is clear that the premature cessation of the current observations will adversely affect the estimation of eta-Earth.

It appears that some type of observations can continue by using only two reaction wheels with occasional help from the reaction jets. Because the pointing precision will be much poorer than obtained previously, it is expected that the photometric precision will be also be substantially degraded. Thus it is extremely unlikely that observations will have sufficient precision to detect additional transits of Earth-size planets in the HZ of G-dwarfs. Therefore a more indirect approach is proposed to improve the reliability of the estimate for eta-Earth. This approach consists of developing an interpolation function that approximates the current results and making additional observations of long-period planets to define an interpolation surface. Clearly, only planets substantially larger than that of Earth can be detected because of the degraded photometric precision. The truncated planetary size distribution for long orbital periods (i.e., periods larger than that for the HZ of each target star) can be used in conjunction with planets that have short orbital periods but have a more complete size distribution. Thus the interpolation function will be based on a data set that includes planets with a full range of sizes, on orbital periods at least as long as those associated with the HZ, and on an appropriate range of stellar properties. This type of problem can be addressed by several methods including simulation, hierarchical Bayes (2), and Approximate Bayesian Computing that allow for complex or non-parametric functions to be used for the interpolation.

¹ These values are based on the definition of the HZ associated with the “Early Venus” level of insolation to that of the “wet Mars” level (3).

As a simple, but illustrative example of an interpolation method: an analytic function is fitted to the observations and then the fitted function is integrated over the ranges of interest (i.e., ~ planet size and insolation for stars similar to the Sun) to estimate the number of “detected” planets. In particular, the analytic function ρ , is fit to the actual number of planets detected in a bin with a size $R \pm \Delta R$ and orbiting a dwarf star with an effective temperature (T_{eff}) that produce a radiant flux at the planet of $S_{\odot} \pm \Delta S_{\odot}$, where S_{\odot} is the value of the Sun’s flux at the orbital distance of the Earth. Then $\rho(R, T_{\text{eff}}, S)$ is integrated over the volume near $R \approx R_{\oplus}$, $T_{\text{eff}} \approx 5780\text{K}$, $S \approx S_{\odot}$ to estimate the number of “detected” planets in the HZ of solar-like stars. It is proposed to select one of the techniques mentioned in the previous paragraph that is best suited to the problem.

Eta-Earth is the ratio of this value to that expected from a calculation of the expected number based on the assumption that every target star has an Earth-size planet in its HZ. See (4, 5, & 6) for discussions of this part of the calculation. Thus ρ and its uncertainties will depend upon the values and uncertainties of the measured data points in and surrounding the region of interest. To enable the calculation of ρ to be based on an interpolation of results rather than on an extrapolation to the periods of the HZ for G dwarfs, it is important to obtain a substantial number of points surrounding the region of interest; i.e., at orbital periods at least as great those associated with the HZ. Thus it is critical to extend the Kepler observations of the targets in the current FOV to catch the next transits of long-period planets.

The detection of long-period planets is particularly sensitive to the loss of even one transit. The loss of transits due to data gaps due to quarterly rolls, “safeing” events, data processing breaks, and noisy periods can cause the number of transits to fall below the minimum needed for detection and at the very least, reduce the SNR signals possibly below the threshold value required for detection. Additional observations can mitigate the effects of these gaps.

Importance of continued observations of eclipsing binaries.

One of the most critical factors in estimating the occurrence frequency of planets from the Kepler observations is the determination of the eclipsing binary (EB) distributions. Their presence in target star apertures is a major source of false-positive events because EBs can mimic planetary transits. The decreasing probability of orbital alignment with increasing orbital period makes it difficult to determine accurate values of their distribution at the periods of interest for the determination of eta-Earth. Continuing the observations of as many as possible of the targets in the Kepler FOV would lead to the discovery of long-period EBs. Note that for these calculations, many of the transit amplitudes will be quite large because they represent stellar eclipses rather than planetary transits. The period and brightness distributions of bright binaries can be used to estimate those of the many dim binaries found in the apertures.

Required photometric precision

Although the photometric precision obtainable from 2-wheel Kepler Mission is not likely to be sufficient to detect Earth-size planets when only the 3 or 4 transits are available, detection of planets with sizes of superEarths and larger might be possible. For planets between the size of a superEarth (1.5 R_{\oplus}) to that of Neptune (3.9 R_{\oplus}), the transit depths range from 0.19 millimagnitude (mmag) to 1.3 mmag for those orbiting G-dwarfs to 0.37 mmag and 2.5 mmag for planets orbiting K5 dwarfs. For transits of long-period orbits, transit durations of solar-like stars have an average duration of 10 hours. If a photometric precision of 0.5 mmag per half-hour sample is obtained, then 20 samples will provide a precision of approximately 100 ppm. To get this level

of precision is likely to require the use of image motion regression (including the use of short cadence data and/or star tracker data), and the use of the local flat field measurements made on detectors prior to the launch of the Mission.

Based on the need to obtain a minimum of a 4σ detection per transit to make a significant contribution to the multi-event statistic, it is strongly recommended that observations of the current Kepler FOV be continued if a photometric precision of 0.1mmag (100ppm) can be obtained for a 10-hour duration transit after correcting for image motion. Continuation of observations of the current targets in the Kepler FOV for the purpose of detecting planetary transits of long-period planets appears unwarranted if it's not possible to obtain precision of 1mmag for a 10 hour transit of a quiet 12th magnitude G dwarf.

Advantages of Continuing the Observations of exoplanets in the Kepler FOV

Increases the value of the Kepler science by detecting longer-period planets

Provides statistics on long-period EBs that are necessary for estimates of the false-positive rate for long-period planets

Continues TTV observations that are needed for mass estimates

Avoids the need to survey a new set of stars to determine their characteristics, eg.; T_{eff} , $\log(g)$, and size.

Improves the reliability of the Kepler Results Catalog by adding new long-period planets, adding long-period planets to already discovered planetary systems, and by reducing the number of false-positives.

Provides data to the large, international group of scientists conducting long-term asteroseismology investigations

Encourages the continued follow up of unconfirmed planetary candidates using spectroscopic, active optics, and speckle observations by ground based telescopes.

Allows the PSP program to proceed

There will be little change to Mission Ops since no sky regions outside the current FOV would be required with the concurrent requirements of thermal and roll stabilization for each new FOV.

Allows an accurate estimate of costs based on current operations and pipeline data analysis.

Although some software modifications would be required to correct for image motion and changing apertures, there will be no need to develop a completely new data analysis pipeline. This allows the Project to use already-trained personnel to make the required changes.

Disadvantages

Either more frequent DSN contacts are required or a modification of onboard software to frequently repoint the spacecraft is required.

Existing software must be modified to select target apertures that change on a daily basis to accommodate the changing spacecraft orientation.

List of Requirements for continuing exoplanet observations in the current FOV.

Download star tracker data to correct for image motion.

Daily repoint the spacecraft to keep the rotation rate of the FOV low (i.e., ≤ 4 pixels at edge of FOV).

Reduce the number of targets to provide the increased number of pixels required for each target;

1) eliminate dim noisy stars that have not shown any promising TCEs

2) preferentially remove targets at edge of the FOV because these targets require large apertures to accommodate large image motion. The released pixels will be used for more promising targets.

Continue observations of the current KOIs. It is highly likely that these targets represent planetary systems that have planets in outer orbits that have not yet been detected.

Keep Threshold Crossing Events for stars that are bright enough and have sufficiently low noise so that transits of planets as small as $1.5 R_{\oplus}$ can be discovered.

Increase the size of the target apertures as a function of distance from the center of the FOV to track images during image drift.

USE OF THE KEPLER FOCAL PLANE

The focal plane will be used in the manner previously used during the prime mission to search for exoplanets: individual target apertures will be used. Updating these apertures will be done on a daily basis and the apertures will be larger to accommodate image drift.

The integration times will not be changed from those used in the prime mission.

The expected data storage need will be similar to that for the prime mission in that the number of pixels returned from the spacecraft will not be changed, but the number of apertures will be reduced.

The class of science targets will be point sources.

The target durations will be for the full duration of the Mission so that the maximum number of transits can be observed for each target.

The length of the science program should be run for at least two years, preferably for four years. This length is needed to obtain a minimum of three transits for orbital periods associated with planets in the HZ of solar-like (i.e., F, G, and K dwarfs) stars. For planets with shorter orbital periods, the increased length of observations makes possible the detection of smaller planets.

The impact of the proposed observations will be of wide spread interest by the public and the scientific community. During the mission operation, frequent discoveries of planets in the HZ are expected. The final result will provide a reliable estimate of eta-Earth and will be of direct import to the design of future missions that will determine the atmospheric composition of Earth-size planets in the HZ of solar-like stars.

References

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